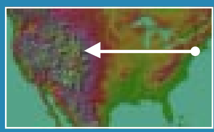


Very Long Baseline Neutrino Oscillation Experiments

for Precise Measurements of Mixing Parameters and CP Violating Effects

Recent exciting results have shown that neutrinos oscillate between their weak eigenstates and thus must not only be massive but their mass and flavor eigenstates do not coincide. This has opened up a whole new area of experimental physics where one strives to precisely measure the mix ing parameters, search for potential CP symmetry violation in the lepton sector and understand secondary effects, such as how the oscillations are effected when the neutrinos pass through matter. It is possible to measure all of the oscillation parameters in a single experiment by employing a 1 MW wide band neutrino super-beam, a very long baseline of 2540 km and a 500 kTon massive far detector.

Goals of the experiment

- Precise determination of the Δm^2_{32} and $\sin^2 2\theta_{23}$
- Detection of $\nu_\mu \to \nu_e$ and measurement of $\sin^2 2\theta_{13}$
- Measurement of Δm^2_{21} and $\sin^2 2\theta_{12}$ in a $\nu_\mu \to \nu_e$ appearance mode (even if $\theta_{13} = 0$)
- Verification of matter enhancement and the sign of Δm^2_{32}
- Determination of the CP symmetry phase δ_{CP}.

The ingredients:

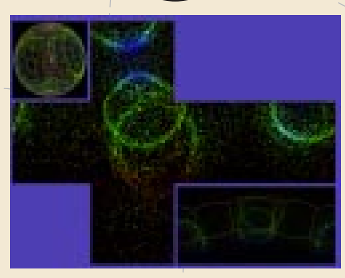
- An intense 1 MW wide band and high energy neutrino spectrum, 0.5-7 GeV.
- A very long baseline >2500 km.
- A massive 500 kTon water Cherenkov far detector.

This allows resolving multiple oscillations, which gives: precise fitting of $\sin^2 2\theta_{23}$ and Δm^2_{32}, absolute event rate uncertainties unimportant (near detector not needed here) and measurement of $\nu_\mu \to \nu_e$ signal over a wide energy range. Different physical effects dominate at different energies so the δ_{CP} and θ_{13} degeneracy can be broken.

- significant signal above 2 GeV where the background is very low.
- sensitivity to matter effects ⇒ determine the sign of Δm^2_{32}
- to measure CP effects which to first order are independent of baseline.

UNO Far Detector

An artist rendition of the UNO detector, which is one possible far detector design. Nominal design parameters: 3 cubical, optically separated, sections each $(60m)^3$, containing 650 (450) kTon total (fiducial) mass, viewed by 57K (15K) inner (veto) detector PMTs corresponding to 10%/40%/10% coverage for the 3 inner detectors and are read-out with waveform digitizers.



Besides providing the features needed for a far detector for this experiment, UNO will produce a vast wealth of physics results as a stand alone detector. It will push proton decay lifetime limits above 10^{34} years for $p \to e+\pi$ (for which a simulated example event is shown), it will precisely measure the parameters relevant to oscillation of atmospheric neutrinos and will be sensitive to solar and supernova neutrinos, both direct and relic.

Neutrino Oscillation Probability

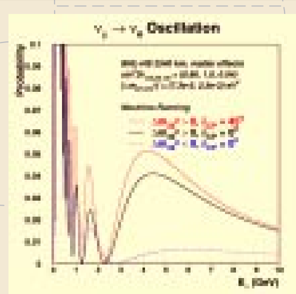
Neutrinos are created as weak eigenstates but propagate as mass eigenstates. These two states are related through a 3 x 3 mixing matrix U such that $v_{weak} = Uv_{mass}$ where $UR_{23}KR_{13}K^*R_{12}$, R_{ij} is a rotation about mass eigenvector $k \neq i,j$ and $K = \mathrm{diag}(e^{-i\delta_{CP}},1,1)$ expresses the amount CP symmetry violation.

In the simplified case of mixing between just two neutrino types propagating through vacuum, the probability for a neutrino of type ν_α to be detected as the other type ν_β is

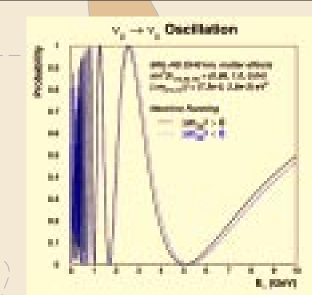
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}$$

Where $\Delta m^2 = m_2^2 - m_1^2$ is the difference between the squared mass eigenvalues, E is the neutrino energy and L is the propagation distance.

Electron neutrinos propagating in matter interact with electrons with larger cross section than muon or tau type neutrinos. This effect can be parameterized as an index of refraction for electron neutrinos. This is called the *matter effect* and leads to an enhancement in the conversion of muon to electron type neutrinos beyond that expected from vacuum neutrino oscillations alone.

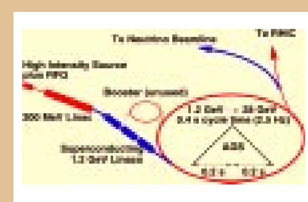


Probability for $\nu_\mu \to \nu_e$ appearance for the best fit parameters from Super-Kamiokande and KamLAND (LMA-I) and a $\sin^2 2\theta_{13}$ 3.5 times below the CHOOZ limit. The three curves show the effect of CP violation as well as changing signs for Δm^2_{32}.



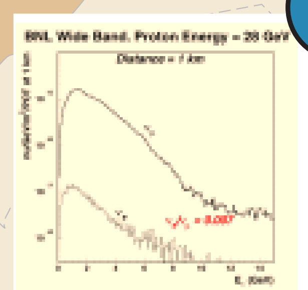
Probability for $\nu_\mu \to \nu_\mu$ disappearance for the same oscillation parameters in the $\nu_\mu \to \nu_e$ case. The two curves show the minor effect of the sign of Δm^2_{32}.

BNL Super-Beam Neutrino Source

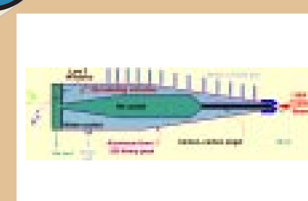


The AGS upgrades necessary to reach 1 MW are shown in blue with existing structures in red. The time structure of the AGS is also shown. The fast 2.5 Hz cycle time and high energy injection into the AGS by the superconducting Linac are the main steps needed to reach 1 MW.

The hill supporting the target station and decay pipe pointing 11° downward towards Homestake. This arrangement proves cheaper than a sloping underground tunnel and allows all major sources of radiation to stay safely above the water table.

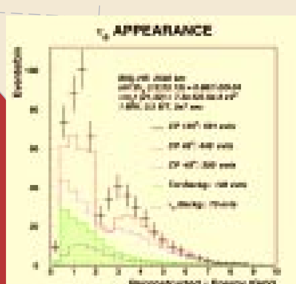


BNL 1 MW Super-Beam neutrino flux, scaled to 1 km from target. This study assumes 5×10^7 seconds (5 Snowmass years) of running with this beam.

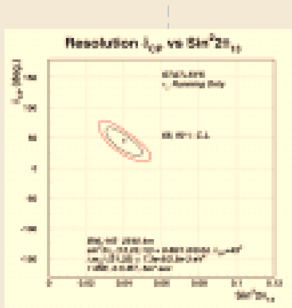


The carbon-carbon target and integrated first horn assembly with the arrow indicating proton beam direction. To remove the heat deposited from the 250 kAmp current and beam interactions in the target and horn assembly, Helium is flowed through the 1 mm annulus between the two and water jets spray the inner conductor.

Results from Appearance

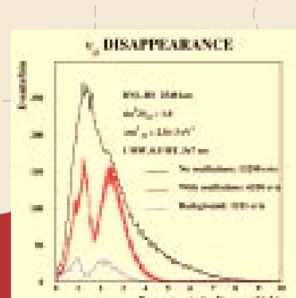


Expected ν_e event rate assuming different values of δ_{CP}. Backgrounds include ν_e from the beam and NC π^0 production.

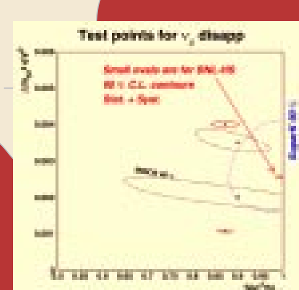


Sensitivity to δ_{CP} and $\sin^2 2\theta_{13}$ at one test point. This is achieved with only running neutrinos. The CP violation effect can be confirmed, and more accurately measured, with subsequent anti-neutrino running.

Results from Disappearance



Expected ν_μ event rate. The oscillated events (red error bars) include both signal and background and have had a 10% energy smearing applied..



Sensitivity to Δm^2_{32} and $\sin^2 2\theta_{23}$ for various test points. Systematic uncertainties, except absolute energy scale which is expected to be 2.5% or better, have been included. For comparison current Super-Kamiokande and expected MINOS allowed regions are shown.

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